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RESEARCH MEMORANDUM

ANALYTICAL AND EXPERIMENTAL INVESTIGATION OF A FORCED-CONVECTION AIR-COOLED INTERNAL STRUT-SUPPORTED TURBINE BLADE

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

WASHINGTON

March 12, 1954

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SUMMARY

Analytical and experimental investigations were conducted to determine the cooling effectiveness and mechanical durability of a forced-convection air-cooled strut-supported blade. Two blades, each consisting of a finned internal load-carrying member, or strut, to which a two-piece base and a two-piece airfoil shell were attached by brazing, were investigated in a modified turbojet engine using an external cooling-air supply.

Experimental results obtained at rated engine speed (11,500 rpm and turbine tip speed of 1300 ft/sec), a turbine-inlet temperature of about 1640° F, and a cooling-air temperature of about 200° F at the blade base indicated that substantial differences between the effective gas temperature and strut temperature were obtained throughout the entire range of coolant-to-combustion-gas flow ratio investigated. For example, at a coolant-to-combustion-gas flow ratio of 0.01, the average strut temperature was about 400° F below the effective gas temperature.

Consideration of the temperature and stress levels of the main load-carrying members of the strut-supported blade and of one of the more favorably cooled shell-supported blades indicated that the strut-supported blade has more promise for operation at higher turbine-inlet temperatures, higher stress levels, and/or lower coolant-to-combustion-gas flow ratios.

The local midchord strut temperatures determined by the analytical method were in good agreement with the experimentally obtained temperatures. The maximum difference between analytical and experimental temperatures was about 35° F when the experimental local strut temperature was approximately 400° F.

INTRODUCTION

Turbine-inlet temperatures and turbine stress levels that are higher than those permitted in present-day turbojet engines are goals that are particularly desirable for engines intended for supersonic aircraft.

These goals may be achieved through the use of turbine cooling. An immediate goal of NACA turbine-cooling research is to obtain air-cooled turbine blades that will operate satisfactorily at turbine-inlet temperatures of about 2000° to 2200° F, which are 500° to 600° F higher than those permitted in present-day engines. It is desirable to maintain the cooling-air requirements at a minimum so that the engine-performance losses, associated with cooling, can be minimized.

As a result of the foregoing goals, the NACA has been investigating various types of air-cooled turbine blades at the Lewis laboratory in order to determine their cooling potential and their applicability to gas-turbine-type engines. 3152

An investigation of shell-supported forced-convection air-cooled turbine blades made of noncritical materials and having corrugated inserts was reported in reference 1. The results indicated that such blades were capable of being operated at current turbine-inlet temperature levels and at cooling-air temperatures of 450° F (approximate compressor-exit temperature for compressor-pressure ratio of 4) for cooling-air-to-combustion-gas flow ratios as low as 0.01. Unpublished analyses have shown that shell-supported blades with corrugated inserts can be operated at turbine-inlet temperatures of about 2000° F and cooling-air temperatures at the blade base of about 470° F with cooling-air-to-combustion-gas flow ratios on the order of 0.02, when the blade is made from a high-temperature alloy.

In the shell-supported blade, the main load-carrying member is the blade shell, which is exposed directly to the hot combustion gases. Another type of blade, in which the main load-carrying member is protected from the hot combustion gases by the blade shell and a layer of cooling air, is known as a strut-supported turbine blade. Analytical investigations of such a blade were reported in reference 2, and the results indicated that the strut-supported blade had more potentiality for being operated at high turbine-inlet temperatures, high stresses, and low coolant flows than did the shell-supported blade. Experimental investigations of a strut-type blade (ref. 3) verified the conclusions made in the analysis of reference 2.

The first strut blade that was experimentally investigated (ref. 3) was built primarily to help verify the theoretical analysis of heat-transfer characteristics of the strut-type blade presented in reference 2. In order to expedite the fabrication and experimental investigations of the first strut blade design, there was no special attempt made to incorporate certain desirable mechanical and aerodynamic features. As a result, the first strut-supported blade design investigated had certain recognized shortcomings such as high cooling-air pressure losses, a dimpled outer surface on the blade shell, and a rather intricate and perhaps undesirable machining process to obtain the strut profile.

In order to improve upon the over-all design of the first strut-supported blade, additional heat-transfer analyses were made and the results incorporated in another strut-supported blade design. This present design as well as the first strut-supported-blade design was based upon the assumption that a minimum strut temperature for a given quantity of cooling air is desirable in order to obtain high rupture and yield strength in the strut. The thermal stresses caused by the large temperature differences between the shell and strut, as well as vibratory stresses, were not considered in design stress analyses. These stresses were not considered because of the complexity of the stress calculations involving the determination of the blade temperature distribution chordwise as well as spanwise. In addition, accurate values of the physical properties of the materials at elevated temperatures, which are not available at present, would also be required in the analysis. It was thought to be more expedient at the present to neglect the effects of thermal and vibratory stresses in strut-supported-blade design considerations and base the initial configurations on the premise that minimum strut temperatures are required.

This report presents the analytical results leading to the design of the present strut-supported-blade configuration and the results of an experimental investigation made on two blades to determine the cooling characteristics of the design. The results of a preliminary endurance investigation of the blades are also presented. The experimental results were obtained in a full-scale turbojet engine that was modified to accommodate two air-cooled turbine blades. Cooling air was supplied to the air-cooled blades from a laboratory air system. Data were obtained at rated engine speed (11,500 rpm and turbine tip speed of 1300 ft/sec) for a turbine-inlet temperature of about 1640° F. The coolant flow was varied so that values of cooling-air-to-combustion-gas flow ratio per blade ranging from 0.01 to 0.08 were obtained. The cooling-air temperature at the base of the cooled blades varied from about 150° to 250° F.

ANALYSIS

Evaluation of Blade Temperatures

The heat-transfer analysis of the strut-supported blade employed in this investigation required determination of the temperature of the blade strut and shell. The methods used to evaluate these temperatures and the factors required are presented in the following sections.

Blade shell and strut temperatures. - The manner of evaluating the temperatures of the strut and shell at the midchord region of the blade consisted of dividing the cross section of the blade at the span position where temperatures are desired into a number of arbitrarily chosen parts, making heat balances at each of these parts, and solving the heat-balance equations. Since the shell and strut temperatures are dependent on the local cooling-air temperatures, an iteration process to determine the cooling-air temperature rise through the blade was required together with the heat-balance equations. The method used to determine the shell and strut temperatures was similar to that described in detail in reference 4. It should be noted that this method is only applicable for determining temperatures in the midchord region of the blade for the reasons cited in reference 4.

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Heat-transfer coefficients. - The average gas-to-blade heat-transfer coefficients, which were used herein to determine the temperatures of the shell and strut, were evaluated according to the method presented in reference 5. The velocity distribution around the turbine blade, which was required to evaluate these coefficients, was obtained by the method described in reference 6. The blade-to-coolant heat-transfer coefficients were evaluated by the use of equation (15) of reference 7. This equation was obtained from a correlation of data of heat transfer to air flowing in tubes.

Coolant temperatures. - The coolant temperatures at the various span locations of the blade were evaluated by the use of equation (D2) of reference 4. This equation relates the temperature rise of the coolant in an incremental length of span to the temperature rise resulting from heat transfer from the hot gases and from rotation. Since the heat transferred to the coolant is dependent on shell temperatures, which in turn are dependent on coolant temperatures, solution of the equation required an iteration process.

Preliminary Blade-Design Considerations

In order to arrive at the present strut-supported-blade design, an analysis was conducted to investigate the heat-transfer characteristic of the strut-supported blades. An insight into the considerations associated with the heat-transfer aspect of the blade design can be obtained from an explanation of the cooling mechanism of the strut. This mechanism can be illustrated by the use of a cross section of a strut-supported blade, as shown in figure 1. (Points o, q, r, s, and t are discussed in Methods.) The heat from the hot gases flowing over the shell is transferred to the shell, then conducted through the shell. A portion of the heat from the shell is transferred directly to the cooling air, while the remainder is conducted through the attachment medium into the primary fins. Some of the heat entering these fins is dissipated to the cooling air, while the remainder is conducted to the

body of the strut. A portion of the heat entering the body of the strut is dissipated directly to the cooling air, and the remainder is conducted to the secondary fins from which it is dissipated to the cooling air. Thus, from the consideration of the cooling mechanism alone, it is apparent that investigations of the effects of attachment area, primary- and secondary-fin thickness, and number of secondary fins are required in the design of the blade. An analytical investigation was therefore conducted to determine the effect of these factors on the
3152 strut temperature and to select a strut design for a particular turbine-blade profile.

Conditions of analysis. - The aerodynamic profile selected is shown in figure 1. The profile is that for a 3/8-span location of a twisted airfoil blade having good turbine-performance characteristics. The analysis to establish the effect of strut geometry on average strut temperature was made at the 3/8-span location because it is believed that this is the critical section of the blade from the temperature and stress viewpoint. A turbine-inlet gas temperature of 2000° F, which results in an effective gas temperature of 1750° F, was considered for design purposes. The coolant-inlet temperature at the base of the blade was assumed to be 500° F. This value was based on an assumed compressor-bleed temperature of 450° F (which is typical for present-day turbojet engines with compressor-pressure ratios of about 4 and with compressor-inlet temperatures of about 80° F) and a 50° F rise in coolant temperature as the cooling air is ducted through the rotor to the blade base. Variations in the number and thickness of secondary fins, thickness of primary fins, and the amount of attachment area between shell and primary fins that were considered in the analysis are given in the following table:

Item	Number of secondary fins	Thickness of secondary fins, in.	Thickness of primary fins, in.	Percent of attachment area
Effect of number of secondary fins	0	-----	0.040	100
	1	0.020	.040	100
	2	.020	.040	100
	3	.020	.040	100
Effect of primary-fin thickness	3	0.020	0.020	100
	3	.020	.040	100
Effect of secondary-fin thickness	3	0.020	0.040	100
	3	.040	.040	100
Effect of attachment contact area between shell and primary fin	3	0.020	0.040	100
	3	.020	.040	50
	3	.020	.040	25

Methods. - The procedure for evaluating coolant and strut temperatures in the midchord region, which was briefly described in Evaluation of Blade Temperatures, is discussed in more detail in reference 4. In this reference, a mathematical and an electrical analogy type solution is given. The mathematical procedure required to obtain the midchord strut temperatures involves the simultaneous solution of a large number of equations. Since the time involved as well as the tediousness of the solution of these equations can be greatly reduced by use of electrical analogy, the analogy was used herein. In this analogy, the thermal resistance of each of the component parts of the strut blade as well as the gas-to-blade and blade-to-coolant thermal resistances are represented by corresponding electric resistances. Voltage values from measurements made on the analog constructed for a strut blade (ref. 4) are analogous to the temperatures of the blade. The average analytical midchord strut temperature used in this phase of the analysis is an arithmetic average of the calculated temperatures at points o, q, r, s, and t (fig. 1), which are identical to similar points shown in reference 4. The lengths of the component parts of the strut blade (see ref. 4 for the component parts considered), which were used to evaluate electric resistances in the analog, were based on average lengths measured for the midchord section of the blade. The values of the average heat-transfer coefficients evaluated in the manner described earlier and the assumed values of coolant and effective gas temperature were also used in the analogy according to the method described in reference 4. It is estimated that the accuracy of the analog results obtained with respect to the mathematical solution is of the order of 1 percent, in accordance with the accuracy achieved in reference 4.

Results of analysis. - The results of the analysis made to determine the effect of variations in strut geometry on strut temperatures for a range of coolant-to-gas flow ratio of 0.01 to 0.07 are shown in figure 2. An indication of the coolant temperature at the 3/8-span position over the range of coolant-to-gas flow ratio investigated is also shown. For each of the four effects investigated, the maximum variation of the coolant temperature for a specific coolant flow was of the order of 20° F. Consequently, for each of the four effects investigated, the indicated coolant temperature is an arithmetic average of the coolant temperatures for the configurations considered. The average strut temperatures shown (arithmetic averages of temperature at points o, q, r, s, and t, fig. 1), which neglected the small effect of radiation from the shell to the strut, indicated several significant trends which are described herein.

The number of secondary fins had the greatest effect in reducing strut temperatures, as shown in figure 2(a). For example, the addition of each additional secondary fin resulted in a reduction in average strut temperature of about 30° F. The difference in strut temperatures between

a strut with no secondary fins and a strut with three secondary fins is of the order of 95° F. For many materials, a reduction in temperature of 95° F at high material temperatures can increase blade life a considerable amount. It should be noted that the large temperature reduction achieved is contradictory to the impression given in reference 2, in which it is stated that "the secondary fins could possibly be eliminated from the design without much loss in cooling effectiveness". The analysis made in reference 2 did not include an investigation of finning as
3152 is reported herein.

The effect of the primary-fin thickness is shown in figure 2(b). The results indicate that a reduction in average strut temperature on the order of 35° F can be achieved by decreasing the primary-fin thickness from 0.040 to 0.020 inch. Since the primary fin supports the shell, it is the mode of conductive heat transfer from shell to strut and consequently determines the magnitude of heat flow. The larger this heat flow, the greater the strut temperature. Since the primary-fin length (distance from shell to strut) is somewhat fixed because of the thickness of the selected airfoil profile, an increase in the thermal resistance to this conductive heat flow can only be obtained by decreasing the primary-fin thickness. The values chosen for primary-fin thickness were based on strength limitations that are discussed in the section Strut configuration evolved. Although no calculations were made for struts having primary fins thinner than 0.020 inch, it seems logical that the rate of decrease in strut temperature would become greater as the thickness was reduced. This is based on the fact that at zero thickness, the strut would be at the same temperature as the coolant since there would be no conduction from the shell to the strut for this hypothetical case.

The effect of secondary-fin thickness (shown in fig. 2(c)) indicated no significant strut-temperature reduction when the fin thickness was reduced from 0.040 to 0.020 inch. This can be explained as follows: The degree of cooling of the strut with the use of secondary fins is dependent mainly on the product of the effective strut-to-coolant heat-transfer coefficient that is used to replace the secondary fin for analysis purposes (see ref. 2) and the area of the fin in contact with the strut. From the effective coefficient equation given in reference 2, it can be shown that for a constant coolant flow the coefficient varies approximately inversely with fin thickness. Thus, if the thickness of the fin is doubled, the effective coefficient is decreased by approximately two. However, the area of the fin in contact with the strut is doubled. Consequently, the product of the fin contact area and the effective coefficient remains approximately the same regardless of fin thickness, and as a result the strut temperature is not affected.

The effect of attachment contact area between the shell and primary fin is shown in figure 2(d). These results indicate that reducing this area from 100 to 25 percent had little effect on strut temperature. This may be explained by considering the conductive heat flow from the shell, through the attachment medium (such as braze material) and primary fin, and into the strut. The magnitude of this heat flow, which determines the strut temperature, is dependent upon the sum of the thermal resistances of the attachment medium and the primary fin. The thermal resistance of the attachment medium is usually small since its length from shell to primary fin is likewise small. However, because of the relatively larger length of the primary fin, its thermal resistance is relatively larger. As a result, a change from 100 to 25 percent on the smaller resistance would result in little change in the sum of these two resistances. However, for very small percents of contact area, the attachment-medium resistance may become large and a reduction in strut temperature may be achieved. For the ideal case, where there is zero percent contact, a strut temperature approximately equivalent to the coolant temperature would result. Although low values of contact area are desired from the heat-transfer viewpoint, other factors determine the contact area required. These factors are described in the subsequent section.

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Strut configuration evolved. - The strut configuration that was evolved by using the previous analysis is shown in figure 3. Cross-sectional views of the strut are shown for the root section and for sections $1\frac{1}{2}$ and $3\frac{1}{2}$ inches from the blade root. The blade incorporating this strut configuration was designed for operation at a turbine-inlet gas temperature of 2000° F, a coolant temperature at the blade base of 500° F, and a blade tip speed of 1300 feet per second.

Preliminary calculations of the shell temperatures and the strength of the shell in the leading- and trailing-edge sections of the blade indicated that five primary fins were required. The spacing of primary fins was dependent upon the number of secondary fins and the spacing between subsequent fins. Because it was desired that the strut design lend itself to readily available fabrication processes (machining, casting, etc.) with a view toward ease of fabrication and that the pressure drop of the coolant be of a reasonable value, a constant spacing of 0.080 inch between consecutive fins was selected. It was also desired to cool the midchord region of the strut as much as possible because the greater amount of strut material, which supports the centrifugal load of the strut and shell, is in this region. As a result of the analysis described previously, three secondary fins were used in the midchord region of the blade. Because of the chordwise length of the strut, space limitations permitted the use of only two secondary fins between primary fins in the leading- and trailing-edge sections of the strut, as shown in figure 3. In view of the results shown in figure 2(c), a 0.020-inch-thick secondary fin was used in order to conform with available fabrication processes and the desire for a light-weight blade. From stress considerations, a taper in the strut is desirable. As a result, the thickness of the strut at the blade root and at $3\frac{1}{2}$ inches from the blade root was selected such that a favorable spanwise stress distribution and blade weight resulted. The strut length of $3\frac{1}{2}$ inches was chosen because calculations indicated that the remainder of the shell that extends from $3\frac{1}{2}$ inches to the 4-inch blade length would support itself. The thickness of the strut at any span position was obtained by connecting the strut profile at the base with the profile at $3\frac{1}{2}$ inches from the base with straight lines. This method was used so that straight-line machining could be used in strut fabrication. From strength and vibrational considerations, it was felt that a 0.020-inch shell was of sufficient thickness. The centrifugal force on the shell dictated the thickness of the primary fins. Because the strut was designed for turbine-inlet temperature operation of 2000° F, the primary fin would be at a relatively high temperature at the point of junction with the shell. Since a noncritical steel (Timken 17-22A(S)) was selected for the strut and fins and since the operating temperature of the primary fin was high, the allowable shear stress of the material would be relatively low as compared with the allowable stress of high-alloy materials at the same temperature level. For this reason, a primary-fin thickness of 0.040 inch was required to support the shell for this blade, even though a cooler strut could be achieved with use of a thinner fin as shown in figure 2(b). For strategic materials, a thinner primary fin would be more feasible from the stress viewpoint. Inasmuch as the results shown in figure 2(d) indicate that little temperature reduction can be attained by reducing the braze contact area between the shell and primary fin from 100 to 25 percent, a continuous braze along the span of the primary fins (100 percent) was chosen. Furthermore, a continuous braze would insure a high safety factor in the brazed joint.

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It should be noted that in the design of this blade, emphasis was placed on cooling the strut as much as possible for a given coolant flow. The reason for this was cited in the INTRODUCTION.

DESCRIPTION AND FABRICATION OF BLADE

Two strut blades were fabricated with the desirable features incorporated as determined by the analysis previously described. The aerodynamic profile of the strut blades was thicker than that of the standard uncooled turbine blades used in the test engine, but the twist of the blades was approximately the same. The chord of the blades was approximately 2 inches and the span approximately 4 inches. The strut blades were of a five-piece construction, consisting of a strut, a two-piece shell, and a two-piece base, as shown in figure 4(a). A cross section of the strut configuration at the 3/8-span position is shown in figure 3(b). The slots in the strut (fig. 3) between the fins were 0.080 inch wide. The primary fins were 0.040 inch thick and the secondary fins, 0.020 inch thick. A clearance of 0.015 inch between the secondary fins and the shell was maintained in order to prevent brazing of the two members while the primary fins were being brazed to the shell.

The struts and bases of the blades were made of Timken 17-22A(S) material, which contains about 3 percent of critical alloying materials, with a viewpoint (held at the time of the blade design) of conserving critical materials. The airfoil shell was formed from 0.020-inch sheet stock of N-155, an alloy containing large percentages of nickel, chromium, and other critical materials. This alloy was used because it could be brazed easily to the strut and because it possessed high strength at relatively high temperatures and good oxidation resistance to avoid the erosion and coating problems which were encountered with shell-supported blades made from noncritical materials (refs. 8 to 10). 3152

The first step in the fabrication of the blade was to cut the outside profile of the strut from a piece of forged stock of Timken 17-22A(S) steel. The next step was to mill the continuous straight-line slots in the strut (fig. 4(a)). The blade bases were then cast in two pieces, and the slots in the bases, corresponding to fin location at the base of the strut, were machined. The struts were then inserted into the base and the units were Nicrobrazed. The formed shell halves were then Nicrobrazed to the strut. In this brazing operation, the leading and trailing edges of the shell halves were butted together so that these regions would be brazed at the point of contact. In addition, the shell halves were flaired at the root so that they would be brazed along the fillet at the blade base (fig. 4(b)). Inspection of the leading- and trailing-edge regions and of the blade shell and base junctions after brazing, however, disclosed poor braze contact at a number of points. These regions were then welded to reduce air leakage. Small cracks, however, developed at the junction of the shell and base after this region was welded. Further welding of cracks was not attempted since it was thought that any leakage through these cracks would be negligible. The final steps in the fabrication were to grind the serrations in the base and to trim the blade to length. The completed blades were then nickel-plated according to the method described in reference 10 to prevent oxidation of the low-alloy-material strut. In order to prevent possible vibration of the shell which extended beyond the end of the strut, two stiffeners extending across the coolant passage were welded to both sides of the shell. Each stiffener was of 0.020-inch thickness and 0.25-inch length and made from N-155. A photograph of the blade components prior to assembly is shown in figure 4(b). A photograph of a completed blade (taken after completion of the investigation reported herein) is shown in figure 5. The weight of the completed strut blade is approximately the same as that of the shell-supported blades and approximately 1/2 the weight of the standard uncooled blades of the test engine.

APPARATUS AND INSTRUMENTATION

Description of engine. - The modified turbojet engine used for the investigation of the two strut-supported blades and the instrumentation to measure the combustion-gas flow were similar to those described in references 11 and 12. The engine was modified to permit cooling of the blades with an external cooling-air supply. The two air-cooled test blades were located diametrically opposite in the turbine rotor with the standard uncooled blades located in the other serrations in the rotor.

Instrumentation of blades. - In order to obtain rotor-blade temperatures, chromel-alumel thermocouples and a slip-ring-type rotating-thermocouple pickup system similar to that described in reference 11 were used in the investigation reported herein.

The chordwise temperature distributions of the strut were obtained by three thermocouples located at the 3/8 span of one of the struts, as shown by points 1, 2, and 3 in figure 3(b). The 3/8-span location was chosen for several reasons: It was thought to be the critical section from stress and temperature consideration; it provided similarity with the span location of thermocouples used on other air-cooled blades investigated; and it permitted comparisons of temperature data obtained on a shell-supported corrugated-insert blade (ref. 1). Spanwise temperature distributions of the strut were not obtained because of thermocouple failures early in the test.

The effective gas temperature (uncooled-blade temperature) was obtained from a thermocouple located at the leading edge and at the 3/8 span of each of two standard uncooled blades.

Cooling-air instrumentation. - The control of the flow of cooling air to the air-cooled blades and the instrumentation necessary for calculation of flow rate were the same as those described in reference 11. The cooling-air temperature at the entrance to the blade base was measured by a thermocouple that was inserted in each of two tubes on the face of the rotor which supply cooling air to the blades, a procedure similar to that described in reference 11.

PROCEDURE

Experimental Procedure

Heat-transfer investigation. - The procedure followed in conducting the experimental heat-transfer runs on the strut blades was similar to that followed in reference 11. Runs were made at rated engine speed (11,500 rpm and turbine tip speed of 1300 ft/sec) and over a range of cooling-air-to-combustion-gas flow ratio from approximately 0.01 to 0.08.

Preliminary investigation of blade durability. - After the experimental heat-transfer data were obtained, the two strut blades were subjected to a preliminary endurance test in order to obtain an insight into the durability of the blade. The blades were subjected to a cyclic type of engine operation. Each cycle consisted of operating the engine at idling speed (4000 rpm and turbine-inlet gas temperature of approximately 1100° F) for 5 minutes, accelerating in 15 seconds to rated engine speed (11,500 rpm and a turbine-inlet gas temperature of approximately 1670° F), and maintaining these conditions for 15 minutes, followed by decelerating the engine to 4000 rpm in 15 seconds. The endurance investigation was conducted at coolant-to-gas flow ratios of 0.05 and 0.03. 3152

Calculation Procedure

Calculated strut temperatures. - The analytically obtained local temperatures of the strut at the 3/8 span and midchord region of the blade, for comparison with experimentally obtained temperatures at the same location, were determined by use of an electric analog, as described in the Preliminary Blade-Design Considerations section of this report. The calculated temperatures were obtained at a location on the strut that corresponded to point s of figure 3(b) (also point s of figs. 9(b) and (c) of ref. 4) and to the thermocouple location at the midchord region of the blade (point 2, fig. 3(b)). The effective gas temperatures at the 3/8 span and the cooling-air temperatures at the blade base which were used in the calculation were those experimentally obtained. The profile of the spanwise variation of the effective gas temperature, which is required for the iteration process in order to determine the temperature rise of the cooling air in the blade, was assumed to be similar to temperature profiles obtained from unpublished results of an investigation of an engine similar to the test engine. Temperatures for the midchord region of the blade were the only temperatures calculated because the theory employed is valid only for the midchord region of the blade, as mentioned in the ANALYSIS section and discussed in detail in reference 4.

Calculated shell temperatures. - The analytically obtained temperatures of the blade shell at the midchord region and at the 3/8 span were also determined by use of an electric analog in the manner described in the ANALYSIS section. The shell temperatures reported herein are the arithmetic average of the calculated temperatures at four representative locations on the shell at the midchord region. The locations selected corresponded to points a, c, e, and g of figure 3(b). (Also to the same points in figs. 9(b) and (c) of ref. 4.)

Experimental average strut temperature. - The average strut temperatures reported herein are the arithmetic average of the temperatures obtained by the three thermocouples located in the strut as shown in figure 3(b).

RESULTS AND DISCUSSION

The experimental and analytical results of the heat-transfer investigation of two air-cooled, strut-supported blades are presented in figures 6 to 8 and are discussed herein. The results of a preliminary endurance investigation of these blades are also discussed.

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Experimental Blade-Temperature Distribution

The variation of the temperatures of the leading-edge, midchord, and trailing-edge regions of the strut at the 3/8-span location with coolant-to-gas flow ratio is shown in figure 6. The data were obtained at a turbine-inlet gas temperature of approximately 1640° F (effective gas temperature of approximately 1420° F) and an engine speed of 11,500 rpm (tip speed of 1300 ft/sec). The data indicate that the temperature difference between the leading edge and the midchord region of the strut (points 1 and 2 of fig. 3) was only about 20° F over the entire range of coolant-to-gas flow ratio. A difference of approximately 180° F occurred between the trailing edge and the midchord region (points 2 and 3 of fig. 3) over most of the flow range. The relatively larger temperature difference between the trailing edge and the midchord region of the strut can probably be attributed to the lack of sufficient secondary fins (because of space limitations) in the thin trailing-edge region. Over the entire range of coolant-to-gas flow ratio investigated, substantial differences between the effective gas temperatures and strut temperatures were obtained. At a coolant-to-gas flow ratio of 0.01, for example, the strut temperatures were on the order of 1000° F, which is about 400° F below the effective gas temperature.

Comparison of Experimental Temperatures and Stresses of Forced-Convection Air-Cooled Strut-Supported and Shell-Supported Turbine Blades

The experimentally obtained average temperatures of the support member of the strut blade over a range of coolant-to-gas flow ratio are shown in figure 7(a) for rated engine speed and an effective gas temperature of approximately 1420° F. The average temperatures of the support member, namely, the shell of a corrugated-insert shell-supported air-cooled blade (ref. 1), are also shown. As expected, the data indicate that the temperatures of the primary support member of the strut-supported blade were considerably lower over the entire coolant-to-gas flow range than the temperatures of the primary load-carrying member (the shell) of one of the more effectively cooled shell-supported blades. At low coolant-flow ratios for example, the difference in temperatures of the primary support members of the two blades is approximately 160° F, whereas, at high coolant flow ratios this difference increases to about 250° F.

The lower operating temperatures of the strut-supported blade are not the sole criteria to be considered in evaluating the blades. Factors such as operating stress level of the blade load-carrying members and the blade material properties need to be considered. As previously indicated, the thermal and vibratory stresses were not considered herein because of the complexity of the calculations and the unavailability of accurate values of physical properties of materials at elevated temperature which are needed in these calculations. Therefore, a method for evaluating the merit of the blades, based on consideration of centrifugal stresses only and on the premise that minimum strut temperatures are desired is presented. The evaluation of the blades on this basis can be illustrated by the use of figure 7(a) and a stress-rupture curve of a representative noncritical alloy, Timken 17-22A(S) steel, as shown in figure 7(b). 3152

The shell-supported and strut-supported blades were compared in order to determine the coolant-to-gas flow ratios required at rated engine conditions; this comparison was made on the basis that the two blades had the same stress-ratio factor (ratio of allowable stress to the calculated centrifugal stress). The comparison was made at the 3/8-span location because this location was thought to be the critical region from the stress and temperature viewpoint. The coolant-to-gas flow ratio of the shell-supported blade for this example was arbitrarily chosen as 0.015. For this value of coolant-flow ratio and the experimental shell temperature shown in figure 7(a), an allowable stress of 58,500 psi is obtained, which results in a stress-ratio factor of $2\frac{1}{3}$ based on a calculated centrifugal stress of 25,000 psi for the shell-supported blade. Since the calculated centrifugal stress of the strut blade is 33,000 psi, the allowable stress based on a stress-ratio factor of $2\frac{1}{3}$ becomes 77,600 psi. For this stress, according to figure 7, the required coolant-to-gas-flow ratio for the strut-supported blade is approximately 0.01, which is approximately 33-percent-less coolant flow than required for the shell-supported blade. As was shown in reference 1, if the blades were operated at a higher effective-gas temperature or a higher cooling-air temperature, or both, the improvement of the strut-supported blade over the shell-supported blade would be even greater.

Comparison of Analytical and Experimental Strut-Supported Blade Temperatures

A comparison of the analytical and experimental local temperatures of the strut at 3/8-span position in the midchord region of the blade is shown in figure 8. The data are presented for rated engine speed (11,500 rpm) and a turbine-inlet gas temperature of approximately 1640° F (effective gas temperature of approximately 1420° F). Analytical temperatures for the shell of the strut-supported blade in the midchord region and at the 3/8 span are also shown.

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The analytically determined local midchord strut temperatures are in good agreement with the experimentally obtained temperatures; the maximum deviation is about 35° F (for a local midchord temperature of approximately 400° F) at a high coolant-to-gas flow ratio, with better agreement being obtained at lower coolant-to-gas flow ratios. The good agreement achieved between the analytical and experimental strut-temperature results indicates that the calculated shell temperatures should also be representative of the actual shell temperature. Present instrumentation techniques did not permit installation of thermocouples on the 0.020-inch shell, so that comparison of calculated and experimental shell temperatures could not be made. The calculated values of shell temperature indicate that at low coolant-to-gas flow ratios the difference in the shell and strut temperatures is of the order of 175° F, whereas at the larger coolant-to-gas flow ratios this difference is increased to about 350° F.

Preliminary Investigation of Blade Durability

After the experimental heat-transfer data were obtained, the two strut-supported blades were subjected to a cyclic endurance test in order to obtain preliminary information on the durability of blade construction. Cyclic-type operation was chosen so that the blades would be exposed to rapid changes in gas temperature and centrifugal-stress level. The two blades were subjected to 10 cycles of operation at a coolant-to-gas flow ratio of 0.05 and 10 cycles at a coolant-to-gas flow ratio of 0.03. The two blades did not fail even when operated with the cracks in the fillet between the shell and blade base, which were described previously. A photograph of one of the blades after termination of the 20 cycles is shown in figure 5. The endurance results reported herein, though very limited, indicated to some extent the satisfactory durability of blade construction.

General Remarks

Although the investigations conducted on blades utilizing the principle of protecting the load-carrying member from the hot-gas stream indicated that blades of this type have a greater potential for operating at higher turbine-inlet temperatures, higher stress levels, and/or lower coolant-flow ratios than the shell-supported blades, considerable investigation and development is still required before the strut-supported blade is satisfactory for service application. For example, more extensive endurance testing of blades at gas temperatures and stress levels higher than those in current engines is required for low coolant-to-gas flow ratios. In addition, other methods of blade fabrication such as casting, forging, and laminating should be investigated with a view toward decreasing the blade weight and increasing the ease of blade manufacture.

SUMMARY OF RESULTS

The following results were obtained from an experimental and analytical investigation to determine the cooling effectiveness and construction durability of the present design of a forced-convection air-cooled strut-supported blade:

1. An analysis to determine the effect of variation of strut geometry on strut temperature for the blade profile chosen indicated that increasing the number of secondary fins, which serve to augment the coolant surface area of the strut, had the largest effect in reducing the temperature of the strut. The thickness of the primary fins, which serve as support members for the shell, had the next largest effect, and the thickness of secondary fins and the attachment contact area between primary fins and shell had little effect. 3152

2. Appreciable cooling of the support member of the strut-supported blade reported herein was obtained. At a coolant-to-gas flow ratio of 0.01, for example, the difference between the average experimental strut temperature and the effective gas temperature was approximately 400° F.

3. Consideration of the temperature and stress levels of the main load-carrying members of the strut-supported blade and of one of the more favorably cooled shell-supported blades indicated that the strut-supported blade has more promise for operation at higher turbine-inlet temperatures, higher stress levels, and/or lower coolant-to-gas flow ratios.

4. Cyclic endurance tests of the blades, though limited, indicated to some extent satisfactory durability of blade construction.

5. Analytically obtained local midchord strut temperatures were in good agreement with experimentally obtained temperatures.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, December 9, 1953

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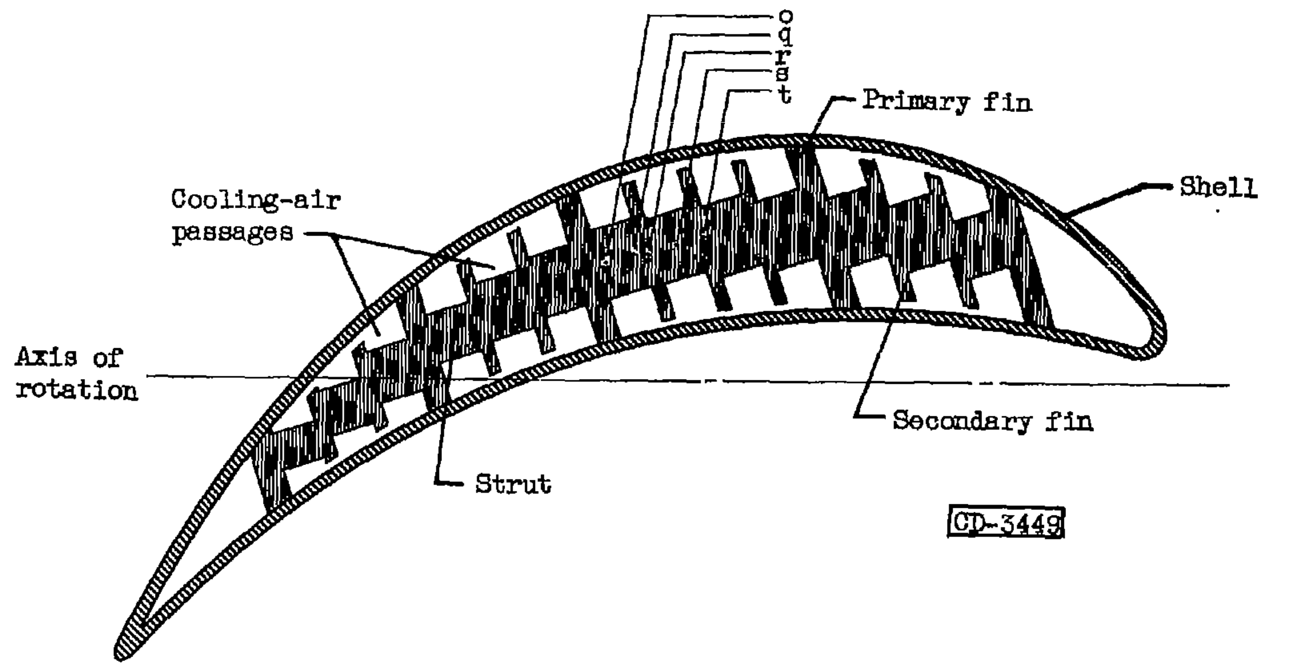

Figure 1. - Cross section of an air-cooled, strut-supported turbine blade. (Location of points for analysis are also shown.)

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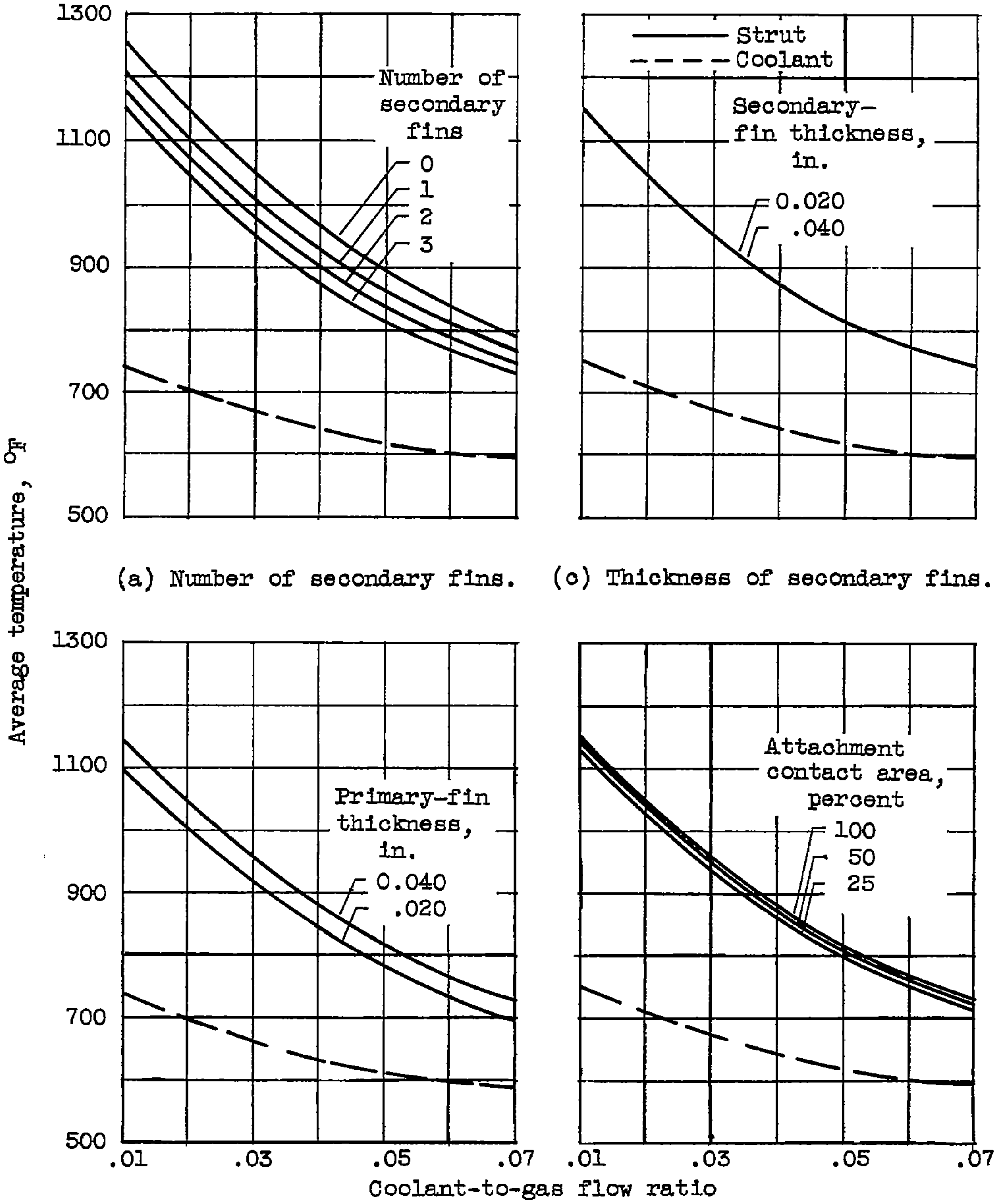
CB-3 back



(a) Number of secondary fins.

(c) Thickness of secondary fins.

(b) Thickness of primary fins.

(d) Attachment contact area.

Figure 2. - Effect of variations of strut geometry on average strut temperature and average coolant temperature in midchord region at 3/8 span. (See table in text for geometric variations.) Effective gas temperature, 1750° F; coolant inlet temperature at blade base, 500° F.

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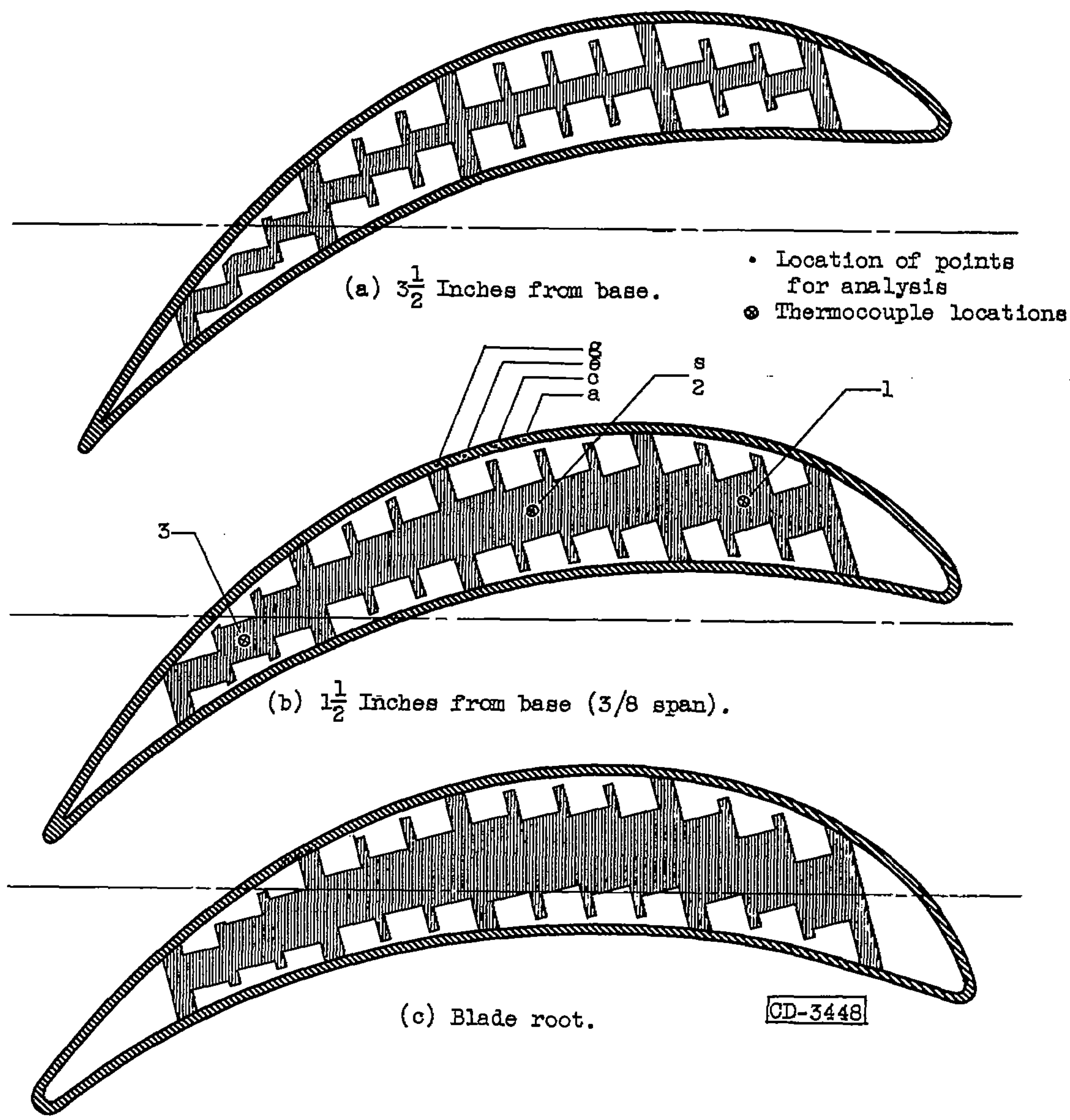

Figure 3. - Strut-supported blade profile at root and at positions $1\frac{1}{2}$ (3/8 span) and $3\frac{1}{2}$ inches from blade root. (Thermocouple locations and locations of points for analysis are also shown.)

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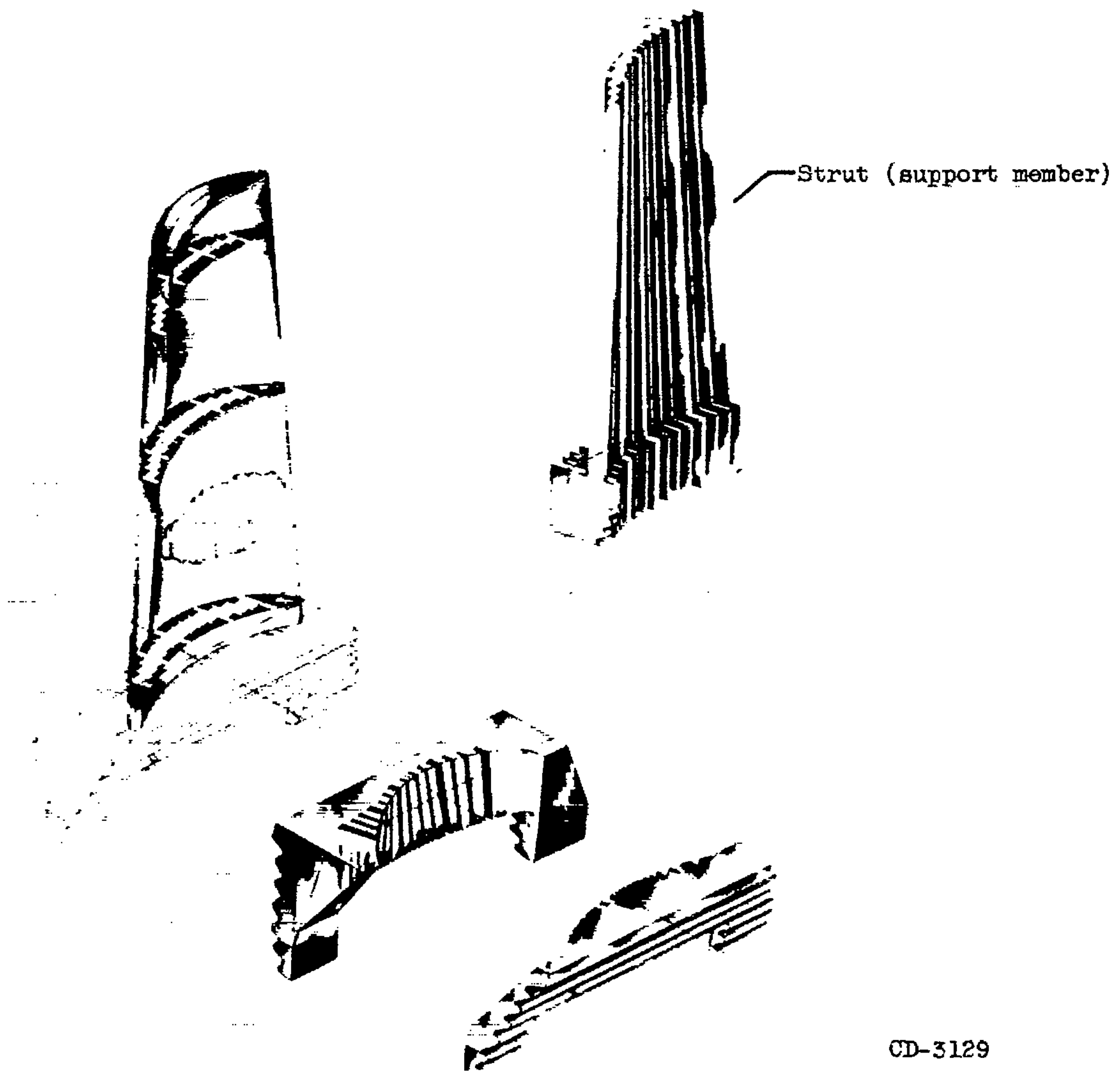
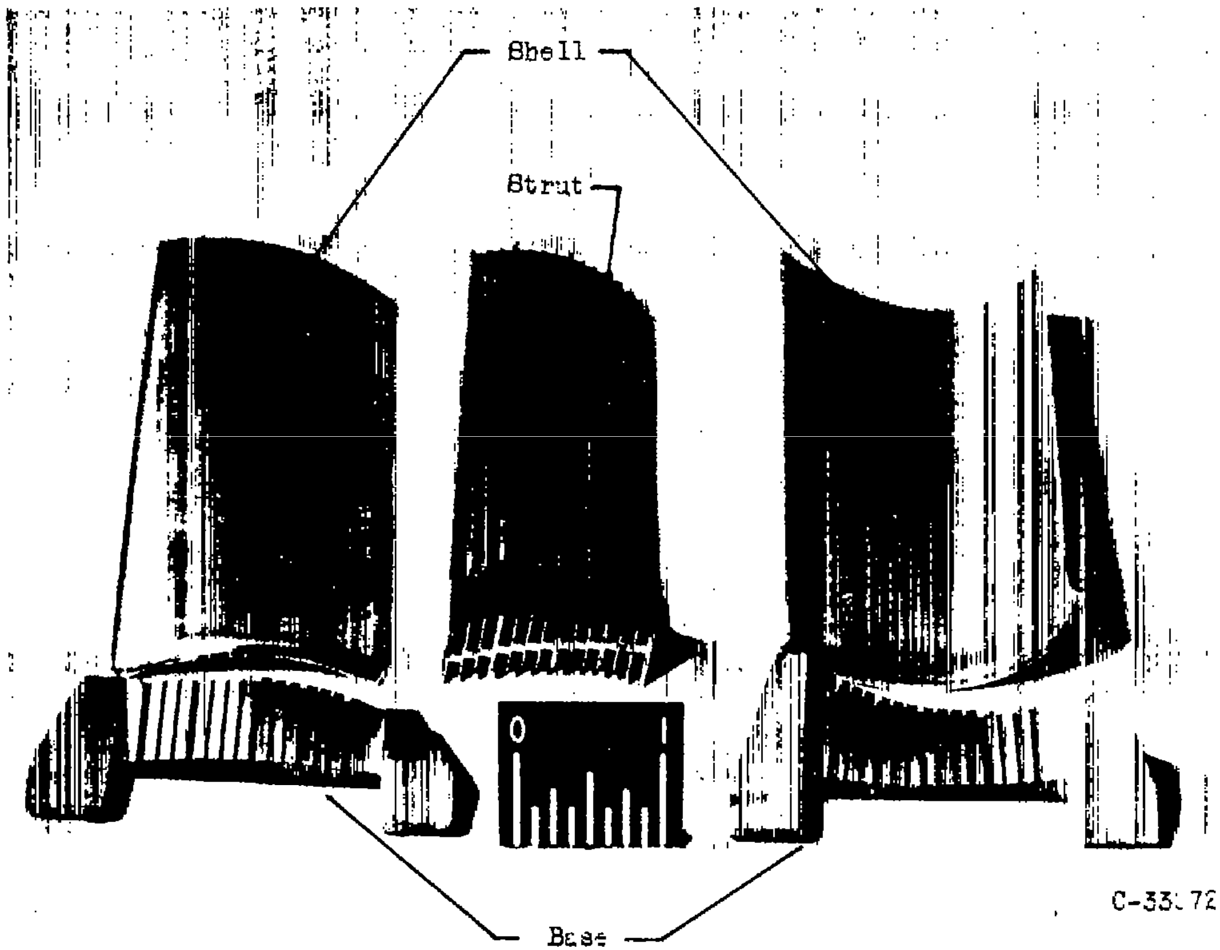


(a) Isometric view.

Figure 4. - Air-cooled, strut-supported turbine blade.



(b) Components of blade before assembly.

Figure 4. - Concluded. Air-cooled, strut-supported turbine blade.

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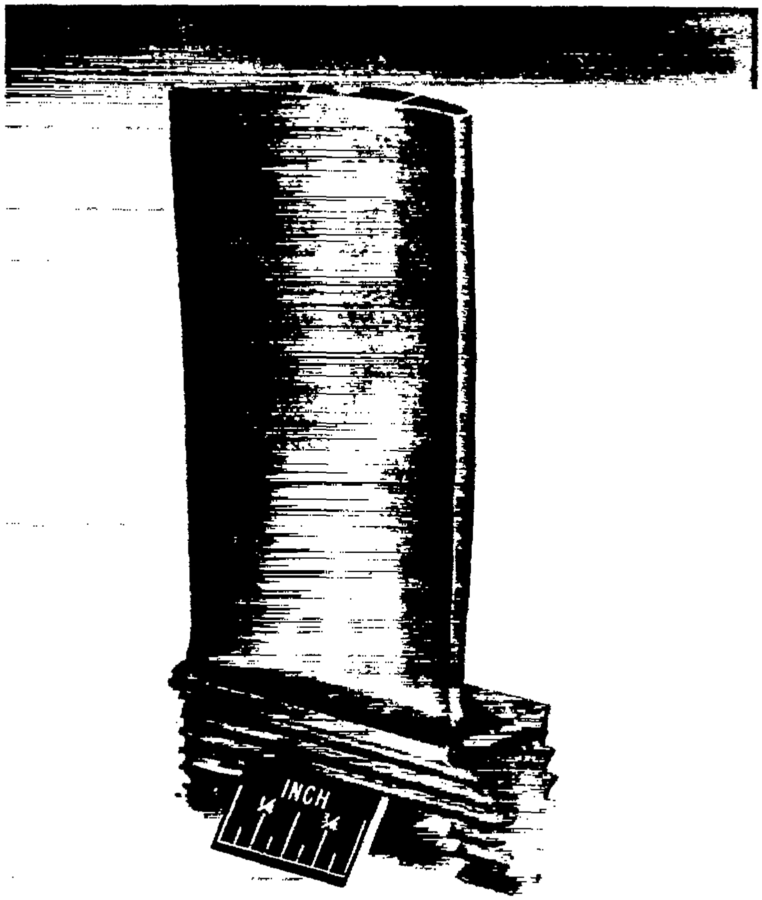

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Figure 5. - Air-cooled, strut-supported turbine blade.

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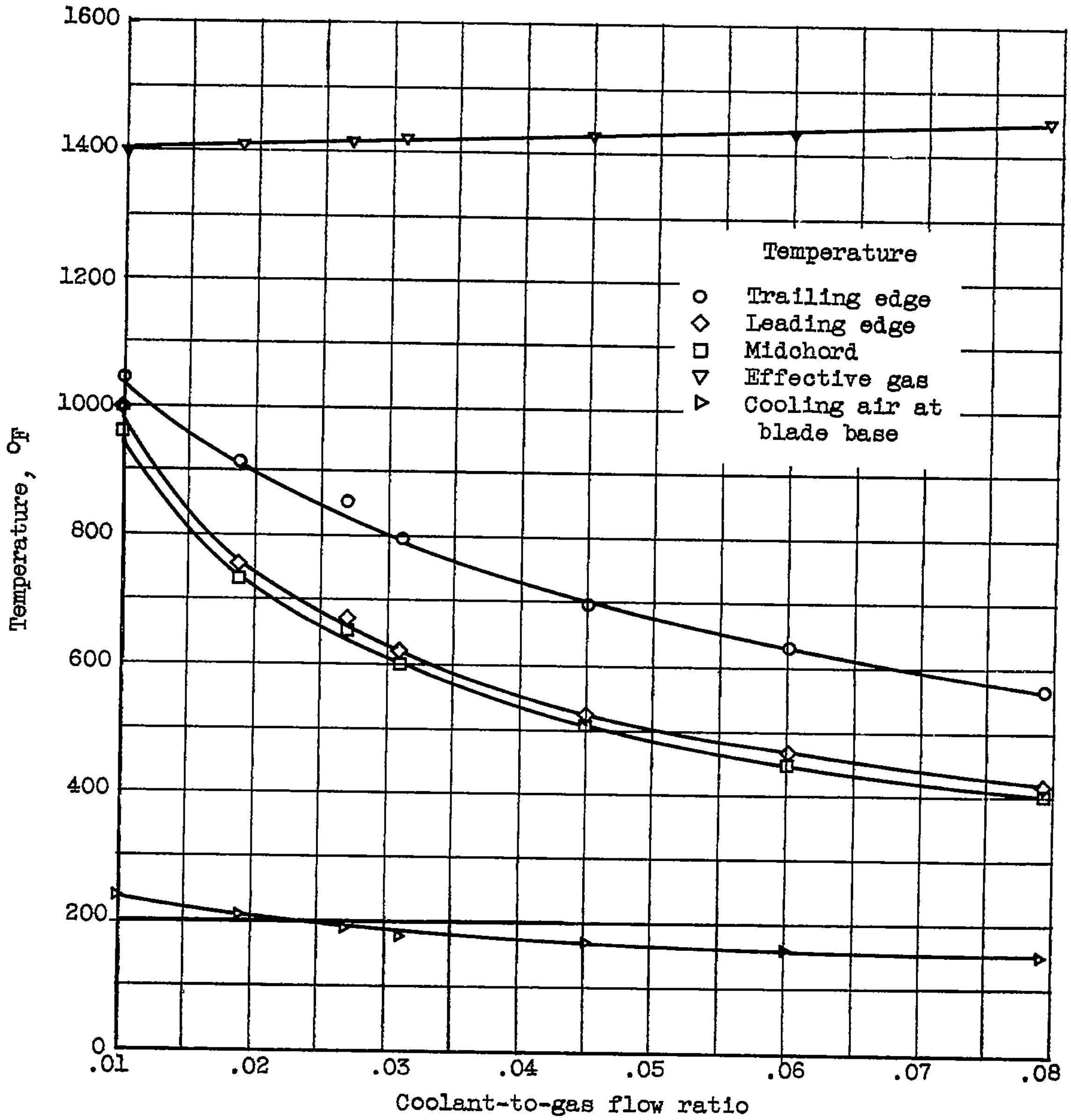
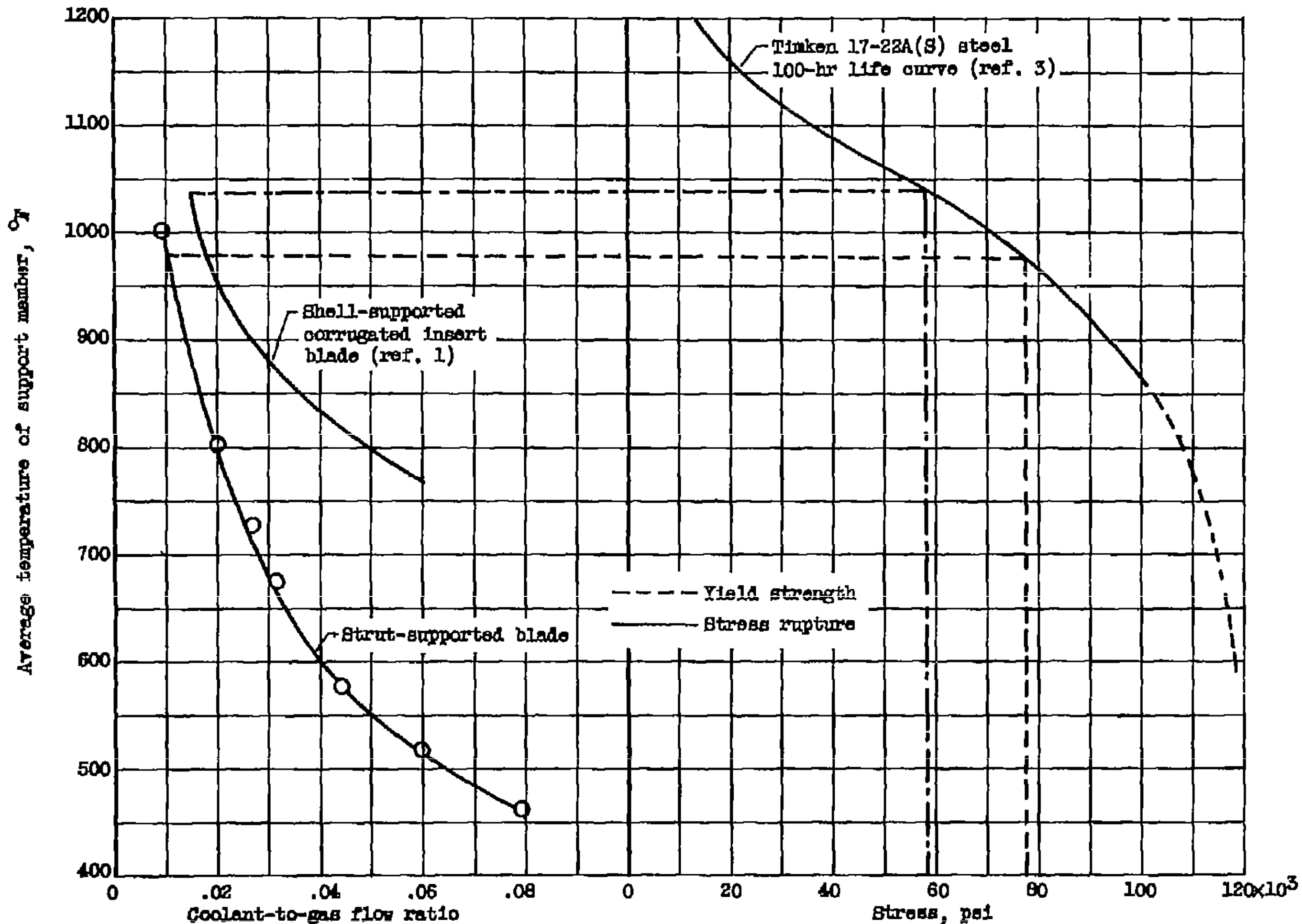


Figure 6. - Variation of experimental strut temperature of air-cooled, strut-supported blade with coolant-to-gas flow ratio at 11,500 rpm. (Effective gas temperature and cooling-air temperature are also indicated.)



(a) Temperature comparison (experimental).

(b) Stress comparison.

Figure 7. - Blade temperatures and stress-to-rupture curve used in comparison of required coolant-to-gas flow ratios for strut-supported and shell-supported turbine blades. Effective gas temperature, approximately 1420° F; coolant temperature at blade base, approximately 200° F; engine speed, 11,500 rpm; stress ratio factor, $2\frac{1}{3}$.

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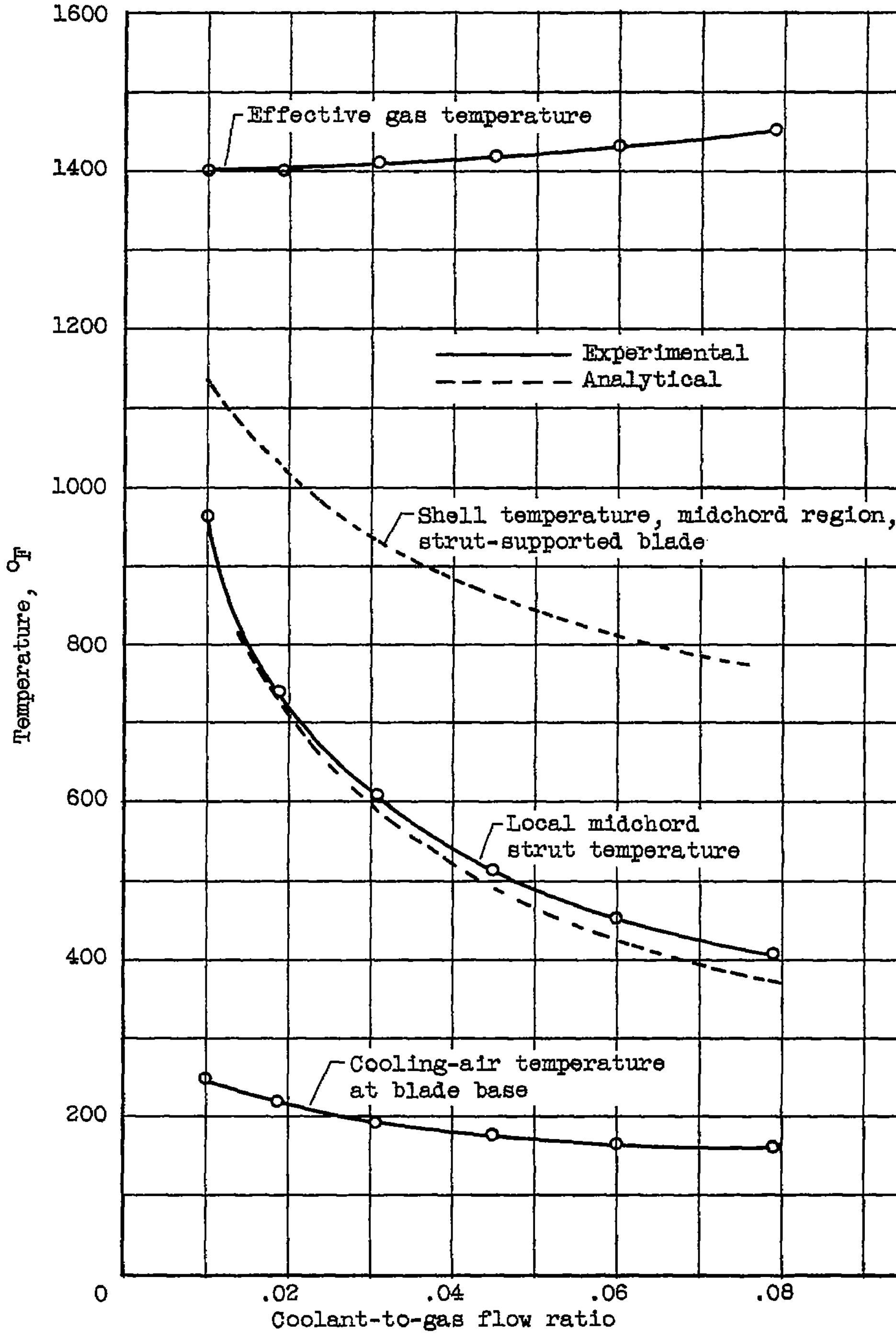

Figure 8. - Comparison of analytical and experimental strut blade temperatures at 3/8 span for range of coolant-to-gas flow ratio at engine speed of 11,500 rpm.

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